

Vertical Structure of the Anomalous 2002 Antarctic Ozone Hole

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ABSTRACT

Ozone estimates from observations by the *NOAA-16* Solar Backscattered Ultraviolet (SBUV/2) instrument and Television Infrared Observation Satellite (TIROS-N) Operational Vertical Sounder (TOVS) are used to describe the vertical structure of ozone in the anomalous 2002 polar vortex. The SBUV/2 total ozone maps show that the ozone hole was pushed off the Pole and split into two halves due to a split in the midstratospheric polar vortex in late September. The vortex split and the associated transport of high ozone from midlatitudes to the polar region reduced the ozone hole area from $18 \times 10^6 \text{ km}^2$ on 20 September to $3 \times 10^6 \text{ km}^2$ on 27 September 2002. A 23-yr time series of SBUV/2 daily zonal mean total ozone amounts between 70° and 80°S shows record high values [385 Dobson units (DU)] during the late-September 2002 warming event. The transport and descent of high ozone from low latitudes to high latitudes between 60 and 15 mb contributed to the unusual increase in total column ozone and a small ozone hole estimated using the standard criterion (area with total ozone $< 220 \text{ DU}$). In contrast, TOVS observations show an ozone-depleted region between 0 and 24 km, indicating that ozone destruction was present in the elongated but unsplit vortex in the lower stratosphere. During the warming event, the low-ozone regions in the middle and upper stratosphere were not vertically aligned with the low-ozone regions in the upper troposphere and lower stratosphere. This offset in the vertical distribution of ozone resulted in higher total column ozone masking the ozone depletion in the lower stratosphere and resulting in a smaller ozone hole size estimate from satellite total ozone data.

1. Introduction

The springtime formation of the ozone hole over the Antarctic continent each year has been a recurring phenomenon since its onset in the early 1980s. Space-based

instruments such as the Total Ozone Mapping Spectrometer (TOMS), the Solar Backscatter Ultraviolet (SBUV/2) instrument, and the Television Infrared Observation Satellite (TIROS) N series Operational Vertical Sounder (TOVS) have been monitoring the ozone hole for over two decades now (Schoeberl et al. 1989; Krueger et al. 1989; Stolarski et al. 1991; Gleason et al. 1993; Lienesch et al. 1996). In the late 1980s and 1990s, the size of the Southern Hemisphere springtime ozone hole, as observed by the SBUV/2 instruments on the National Aeronautics and Space Administration's

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(NASA's) *Nimbus-7* and the National Oceanic and Atmospheric Administration's (NOAA's) polar-orbiting satellites, had been increasing fairly steadily since the early 1980s, with one notable exception, an unusually small ozone hole in 1988. The ozone hole in 1988 was small due to anomalously high eddy activity (horizontal transport of ozone from mid- to high latitudes) and an associated polar warming that evaporated the polar stratospheric clouds (PSCs) and reduced the chlorine activation essential for ozone depletion (Schoeberl et al. 1989; Krueger et al. 1989). Similar but more intense anomalous stratospheric weather patterns resulted in a 2002 polar vortex that split into two regions in the mid-stratosphere in the last week of September (Allen et al. 2003; Weber et al. 2003; Sinnhuber et al. 2003). The vortex in the midstratosphere was displaced and misaligned with the less distorted vortex below in the lower stratosphere. This event caused the 2002 ozone hole to dissipate early without growing to the usual size ($\sim 12\text{--}21 \times 10^6 \text{ km}^2$) seen during the month of October in the 1990s and 2000 and 2001.

In this paper, we use ozone estimates from observations by the *NOAA-I6* SBUV/2 and TOVS instruments to describe the vertical structure of atmospheric ozone in the anomalous 2002 polar vortex. The SBUV/2 observations provide total column ozone and ozone amounts in 12 layers, surface to near 0.1 mb (Bhartia et al. 1996). They provide reliable total ozone and layer retrievals in the mid- to upper stratosphere (above 24 km), while layer retrievals below 24 km depend on the total ozone and the a priori profile. The TOVS ozone retrievals, on the other hand, provide partial column ozone estimates between 0 and 24 km, except during major warming events when the upper limit of its retrieval sensitivity drops to the vicinity of 20 km (Neuendorffer 1996). We use the complimentary information provided by the two instruments, SBUV/2 mid-to-upper stratosphere ozone retrievals (UOZ), and TOVS upper troposphere and lower stratosphere ozone retrievals (LOZ), to analyze the vertical structure of the 2002 ozone hole. Annual Southern Hemisphere winter summaries using this information are available for each December (available online at http://www.cpc.ncep.noaa.gov/products/stratosphere/winter_bulletins/).

2. Data and analyses

a. *NOAA-I6* SBUV/2

The version 6 SBUV/2 operational ozone-processing algorithm uses nadir radiance measurements at 12 discrete wavelengths (ranging from 252 to 340 nm) to retrieve total and profile ozone (Bhartia et al. 1996). Total ozone is derived using measurements at 313, 318, 330, and 340 nm using a lookup table approach. Ozone profiles are retrieved by inverting the radiances measured at the eight shorter wavelengths (252, 274, 283, 288, 292, 298, 302, and 306 nm) together with an error covariance matrix and an a priori profile constraining

the retrievals. The SBUV/2 ozone profiles are reported from the surface to the top of the atmosphere in Umkehr layers that are approximately 5 km thick. However, as is common to most of the backscatter ultraviolet (BUV) ozone retrieval techniques, the process of inverting SBUV/2 radiances to obtain vertical ozone profile leads to errors when the true profile is very different from the a priori profile (Bhartia et al. 1996). While the errors in the ozone profile retrieval are only on the order of 5% near 10 mb and above, the errors can be 15% or larger near 100 mb and below. For the 2002 Southern Hemisphere warming event, the surge of ozone resulted in ozone profiles much different from the a priori profiles. For these conditions, we have assessed the uncertainties in the SBUV/2 ozone profile retrieval by computing radiances from the observed ozonesonde profile on 27 September 2002 and using those radiances in the SBUV/2 algorithm to retrieve an ozone profile. To do this, we first reduced the ozonesonde profile obtained at high vertical resolution to the coarser resolution of SBUV/2. This profile was used in the SBUV/2 forward model to compute radiances at the eight shorter wavelengths. The computed radiances were then used in the SBUV/2 retrieval (inverse) model to generate an ozone profile. Figure 1a shows the actual ozonesonde profile at a SBUV/2 Umkehr layer resolution and the SBUV/2 retrieval obtained using radiances computed from the ozonesonde profile. The difference between the two profiles as a function of Umkehr layer is shown in Fig. 1b. Consistent with the analysis by

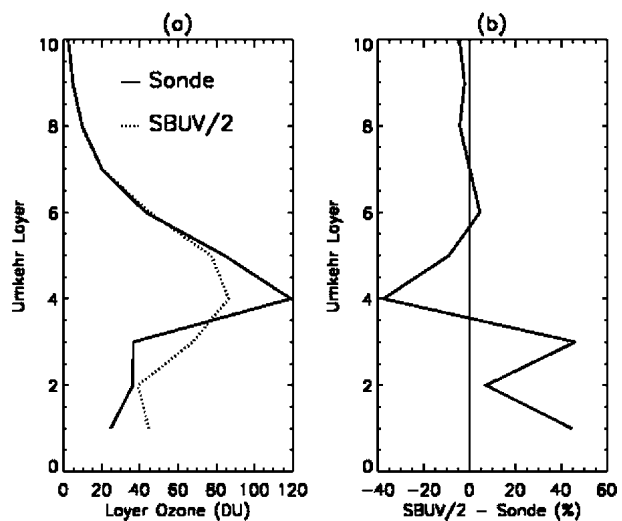


FIG. 1. Response of the SBUV/2 retrieval algorithm to ozone changes in the lower stratosphere. SBUV/2 ozone profile retrieved using radiances computed with ozonesonde profile measured over the South Pole on 27 Sep 2002. (a) Individual layer ozone amounts in DU are for each Umkehr layer. The ozone increase in layer 4 (64 to 32 mb) of ozonesonde profile (solid line) is not accurately resolved in the SBUV/2 retrieval (dashed line). (b) The difference between the two profiles in % plotted for each Umkehr layer. Individual layer retrievals are accurate (with less than 10% errors) in layers 5 and above (above 32 mb).

Bhartia et al. (1996), the SBUV/2 algorithm in this case could not completely retrieve the ozone profile enhancements observed in the ozonesonde Umkehr layer 4 (64 to 32 mb). The SBUV/2 retrieved ozone amount in layer 4 is underestimated by 35%; the algorithm distributed the increased ozone present in the layer 4 of ozonesonde data into SBUV/2 layers 1, 2, and 3. For this reason, the SBUV/2 individual layer retrievals below 32 mb are not recommended for use in process studies (only the integrated partial columns are). Individual layer retrievals from layers at and above 32 mb are within 10% of the ozonesonde profile, similar to errors expected from analysis by Bhartia et al. (1996).

The quality of the SBUV/2 operational ozone product is maintained by monitoring calibration changes and updating the instrument characterization when necessary. Some calibration parameters, such as changes in detector gain range ratio, are monitored and updated daily (Kondragunta et al. 2000). Other calibration parameters, such as changes in solar diffuser plate reflectivity and changes in detector nonlinearity correction, use extrapolated characterizations and are updated less frequently (Hilsenrath et al. 1995; Ahmad et al. 1994). The latest calibration update for *NOAA-16* SBUV/2 was implemented in June 2002. This calibration update accounted for time-dependent changes in instrument sensitivity, solar diffuser plate degradation, and solar activity. The time dependence, generated by using the analysis of the in-flight data from the launch in September 2000 through May 2002, was extrapolated to allow operational processing of ozone data through the end of December 2002. The accuracy of the SBUV/2 total ozone estimates over this time period, determined by comparing with ozone measurements made by a network of ground-based Dobson stations, is 2%. The accuracy of the SBUV/2 profile ozone in the mid- to upper stratosphere, determined by comparing with ozone measurements made by other space-based [e.g., the Stratospheric Aerosol and Gas Experiment II (SAGE II)] and ground-based instruments (e.g., lidar and microwave) is approximately 5%.

b. *NOAA-16* TOVS

The current operational algorithm for TOVS is based on a two-layer retrieval using High Resolution Infrared Radiation Sounder (HIRS) 9.7- μm brightness temperature measurements (Neuendorffer 1996). Although TOVS provides total column ozone, it is primarily sensitive to partial column ozone changes between 0 and 24 km. The partial column sensitivity of the TOVS 9.7- μm radiances to rapid ozone changes, as observed during warming events, drops to 20 km. The quality of the TOVS operational ozone product is maintained by monitoring changes in instrument sensitivity using an onboard blackbody calibration source. Global ozone retrievals at a nadir resolution of 50 km \times 50 km are performed twice daily. Comparisons of 2002 TOVS partial column retrievals with those of ozonesonde

measurements made at a few stations in the Southern Hemisphere tropical region show that they are accurate at the 10% level. The accuracy of ozonesonde data, Southern Hemisphere Additional Ozonesondes (SHADOZ), used in that analysis is $\sim 5\%$ (Thompson et al. 2003).

3. Southern Hemisphere 2002 ozone hole anomaly

Figure 2 shows daily zonal mean SBUV/2 total ozone and TOVS LOZ for 50°–60°, 60°–70°, and 70°–80°S for *Nimbus-7*, *NOAA-9*, -11, -14, and -16. The SBUV and SBUV/2 observations have been adjusted to *NOAA-9* as a standard to account for intersatellite offsets according to the methodology developed by Miller et al. (2002). The figures show five curves corresponding to SBUV/2 total ozone amounts for 2002 (red), 1988 (blue), 1979 (purple), and TOVS LOZ for 2002 (green) and for 2001 (pink). The shaded region corresponds to the range of the SBUV/2 total ozone data from 1979 to 2001. In the latitude band 70°–80°S, daily zonal mean total ozone values for August through September 2002 are higher than the data from 1979–2001, which include the preozone hole years of 1979, 1980, and 1981 and the anomalous year of 1988. The *NOAA-16* daily zonal mean total ozone values of ~ 385 Dobson units (DU; 1 DU = 2.89×10^{16} molecules cm^{-2}) from 25 September to 1 October 2002 were a record high for the full observation period of 23 yr. The late-September 2002 high-ozone anomaly observed by *NOAA-16* was 109 DU higher than the *Nimbus-7* observations in 1988. It is important to note that the total ozone amounts in 2002 were also higher than those observed in the preozone hole year of 1979. However, for October and November, total ozone amounts in the two anomalous years (1988 and 2002) are comparable. Ozone observations are consistent with the meteorological processes in these two years. While the polar vortex in 1988 was weakened by warming and the ozone hole was shallow, the polar vortex in 2002 was pushed off the Pole due to unusually high wave activity (Sinnhuber et al. 2003). The 2002 daily zonal mean values between 60° and 70°S were also higher than those observed between 1979 and 2001 through mid-October, but afterward the 2002 values are comparable to other years. For 50°–60°S, the 2002 values are comparable with those in previous years during the entire ozone hole time period. The high ozone that typically surrounds the Antarctic ozone hole from 60° to 40°S moved into higher latitudes in 2002 and increased their zonal mean ozone values. The TOVS LOZ curve for 2002 (green curve in Fig. 2) shows similar features (maxima and minima) exhibited by the SBUV/2 2002 total ozone curve at all three latitude bands, including the sharp increase in the last week of September observed in the latitude band 70°–80°S. This is because the zonal mean includes data from both inside and outside the vortex. In early October 2002, although the vortex moved toward the center of

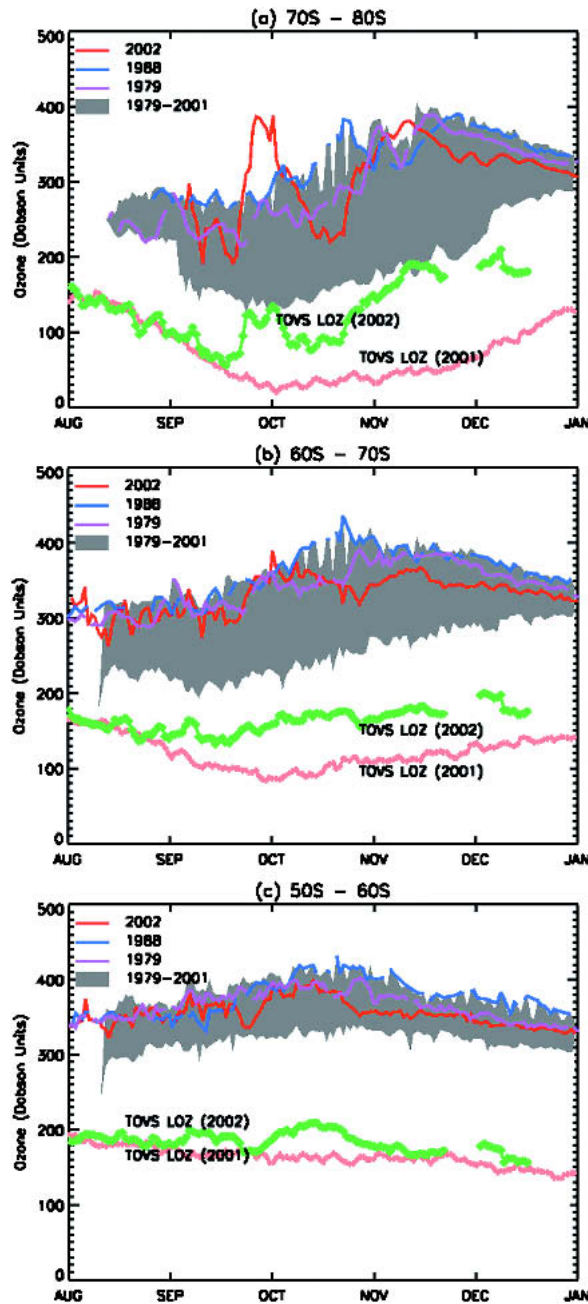


FIG. 2. (a) Daily zonal mean total ozone for latitude band 70° – 80° S. The shaded region is for SBUV/2 data from *Nimbus-7*, *NOAA-9*, *-11*, *-14*, and *-16* for 1979–2001. The red curve is for *NOAA-16* 2002, the blue curve is for *Nimbus-7* 1988, and the purple curve is for *Nimbus-7* 1979. TOVS partial column (DU) between 0 and 20 km for 2002 and 2001 are also shown in green and pink, respectively. (b) Same as in (a), but for latitude band 60° – 70° S. (c) Same as in (a), but for latitude band 50° – 60° S.

the South Pole and was symmetric, the TOVS LOZ zonal mean values remained higher than those observed in 2001, and by late October 2002, the TOVS LOZ values started to increase. This is in contrast to the broad TOVS LOZ minimum observed in 2001 where

TOVS LOZ values did not start rising until early December. This is probably indicative of a slowing in ozone depletion after the major warming. Hoppel et al. (2003) reported similar findings in their Polar Ozone and Aerosol Measurement (POAM) observations of the 2002 ozone hole. Figure 3 shows SBUV/2 daily zonal mean partial column ozone between 24 and 54 km (UOZ) for the same 10° latitude band 70° – 80° S. Again, the late-September spike and a minimum in mid-October SBUV/2 UOZ in the latitude band 70° – 80° S in 2002 are similar to those seen in total ozone (Fig. 2a). As was noted for TOVS LOZ, the late-September 2002 spike in SBUV/2 UOZ is also due to averaging of the measurements made inside and outside the vortex.

To distinguish between the contribution of transport and chemistry to the high ozone observed over the Antarctic continent during the warming event of 2002, and to isolate the nature of daily ozone variations inside the vortex, we separated the data into measurements made inside and outside the vortex by using potential vorticity (PV) estimates to define the location and shape of the vortex. For the vortex in the lower stratosphere, we used a PV contour of -32 potential vorticity units (PVU; $1 \text{ PVU} = 1.0 \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$) at the 450 K potential temperature surface to define the edge of the vortex. For the middle and upper stratosphere, we used PV contours of -160 , -300 , and -500 PVU at 650, 850, and 1000 K potential temperature surfaces, respectively, to define vortex boundaries in Umkehr layers 5, 6, and 7 following Kalnay et al. (1996). Figure 4 shows vortex-averaged TOVS LOZ values for 2002 and 2001. In late September, when the vortex was elongated and displaced from the Pole, the vortex-averaged TOVS LOZ values are much lower than the zonal mean TOVS LOZ values (shown again in this figure for

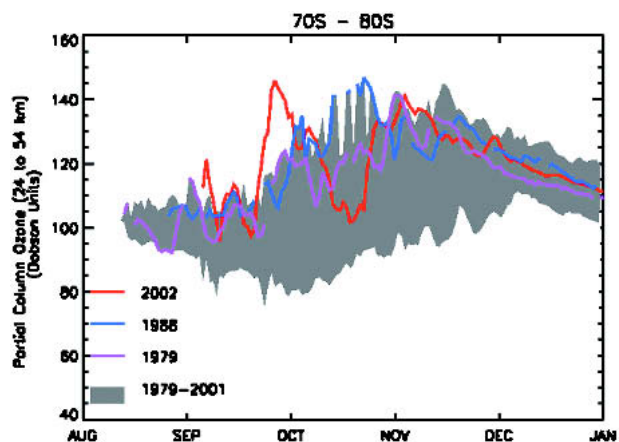


FIG. 3. Daily zonal mean SBUV/2 partial column ozone (24 to 54 km) for the latitude band from 70° to 80° S. The shaded region is for data from *Nimbus-7*, *NOAA-9*, *-11*, *-14*, and *-16* for the years between 1979 and 2002. Data for *NOAA-16* 2002 are shown as a red curve, data for *Nimbus-7* 1988 are shown as a dark blue curve, and data for *Nimbus-7* 1979 are shown as a purple curve.

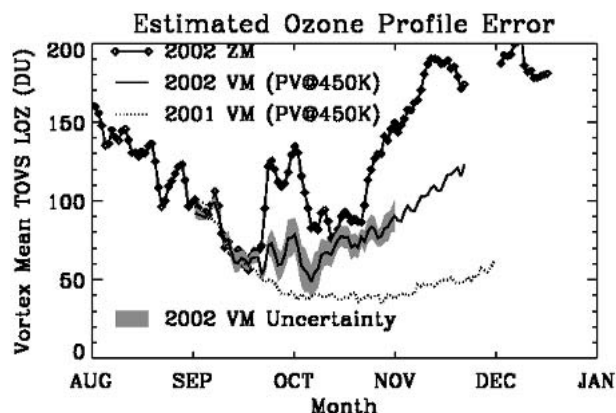


FIG. 4. Vortex-averaged TOVS LOZ amounts for 2002 (solid line), 2001 (dotted line), and 70° – 80° S zonal mean TOVS LOZ amounts for 2002 (diamonds). To compute the ozone mean inside the vortex, the vortex was defined as the area encompassed by PV contours less than -32 PVU at 450 K. The shaded region indicates the uncertainty in the vortex-averaged ozone amounts for Sep and Oct 2002. The spike in the vortex mean TOVS LOZ is probably due to cross-vortex mixing of high ozone from the nonvortex region. It is, however, smaller than the zonal mean TOVS LOZ spike. Until the warming event in late Sep 2002, ozone values inside the vortex are similar to values in 2001, indicating that photochemical ozone loss was similar. After the warming event, the TOVS LOZ values increase, indicating the gradual breakup of the vortex in the lower stratosphere.

comparison) yet show a small spike. This is probably due to cross-vortex mixing of high ozone from the non-vortex region. Although Manney et al. (2005) and Allen et al. (2003) showed that the vortex in the lower stratosphere was displaced from the Pole but intact, the spike in the vortex-averaged partial column TOVS LOZ amounts during the time of warming indicates some cross-vortex transport of ozone. Analysis of POAM-III ozone data reported by Hoppel et al. (2003) and Randall et al. (2005) shows similar findings. It should be noted that when the vortex elongated into two distinct lobes, TOVS LOZ inside the bigger lobe was much lower than the ozone inside the smaller lobe. For example (as will be shown later in Fig. 9), on 25 September 2002, TOVS LOZ amounts inside the smaller lobe were about 50 to 70 DU (probably due to cross-vortex mixing), while TOVS LOZ amounts inside the bigger lobe were only 20 to 50 DU. Note that the smaller lobe further weakened and diminished soon after the warming event, while the larger lobe survived. Until the time of warming, the gradual decrease in ozone in August and September inside the vortex was similar to the decrease in 2001, indicating photochemical destruction of ozone. Although we used only the 450-K potential temperature surface to describe vortex properties in the entire lower stratosphere when computing vortex-averaged ozone, the spike in the vortex averaged TOVS LOZ in late September is not due to the uncertainties associated with its estimates. Even after adding in uncertainty from the assumption of the use of PV

fields at 450-K potential temperature surface to represent the polar vortex in the lower stratosphere (see the shaded region in Fig. 4), the spike indicating the cross-vortex transport is still prominent.

Figures 5a–c show vortex-averaged SBUV/2 ozone values in different layers of the middle and upper stratosphere for 2002 and 2001. During the time of warming, in Umkehr layer 5 (32 and 16 mb), the vortex averaged ozone shows a smaller spike (not as big as the one in the zonal mean), consistent with the presence of extravortex air inside the vortex. In Umkehr layers 6 (16 and 8 mb) and 7 (8 and 4 mb), the vortex-averaged ozone and zonal mean ozone values are similar. Since the vortex extended into lower latitudes in these layers and the vortex boundary weakened, mixing of air parcels across the vortex boundary might have increased the ozone values inside the vortex. This is in agreement with findings that the vortex boundary weakened and extended into the midlatitudes (Allen et al. 2003; Randall et al. 2005; Glatthor et al. 2005) in the middle stratosphere. In fact, the minimum ozone values observed inside the vortex for Umkehr layers 6 and 7 show a sharp increase (50% and 100%, respectively) during the warming event (Figs. 5d–e), while the increase is not as sharp in layer 5 (only 30%). After the warming event, when the larger lobe reintensified and moved back over the Pole, ozone values decreased for a while until late October. After that, the ozone values started to increase rapidly, especially in Umkehr layers 6 and 7. The vortex in these layers dissipated by late October, while the vortex in Umkehr layer 5 survived through early November. This is consistent with the top-down dissipation of the polar vortex. In 2001, when the vortex was symmetric and centered over the Antarctic continent, one would expect the zonal mean ozone between 70° and 80° S to be similar to the vortex mean. But, as is evident in Fig. 5, the values are different, with vortex-mean values higher than the zonal mean values although the shapes of the curves are similar. This is because, in 2001, the vortex edge extended beyond 70° S and the averaging takes into account higher ozone values near the edge of the vortex as well. In summary, the 2002 vortex-averaged TOVS LOZ shows cross-vortex mixing on the smaller side of the elongated vortex in late September, and the 2002 vortex-averaged SBUV/2 UOZ values show a strong peak during the warming event in late September in layers 6 and 7, implying that the split vortex that extended into the midlatitudes had significant cross-vortex transport. The observed spikes in zonal mean SBUV/2 UOZ partial columns in late September during the warming event are consistent with other studies (Hoppel et al. 2003; Randall et al. 2005; Glatthor et al. 2005).

The increase in ozone has been shown to be due to the transport of high ozone from low latitudes to high latitudes outside of the vortex region (Allen et al. 2003; Sinnhuber et al. 2003; Manney et al. 2005). Consistent with these studies, cross sections of SBUV/2 ozone mix-

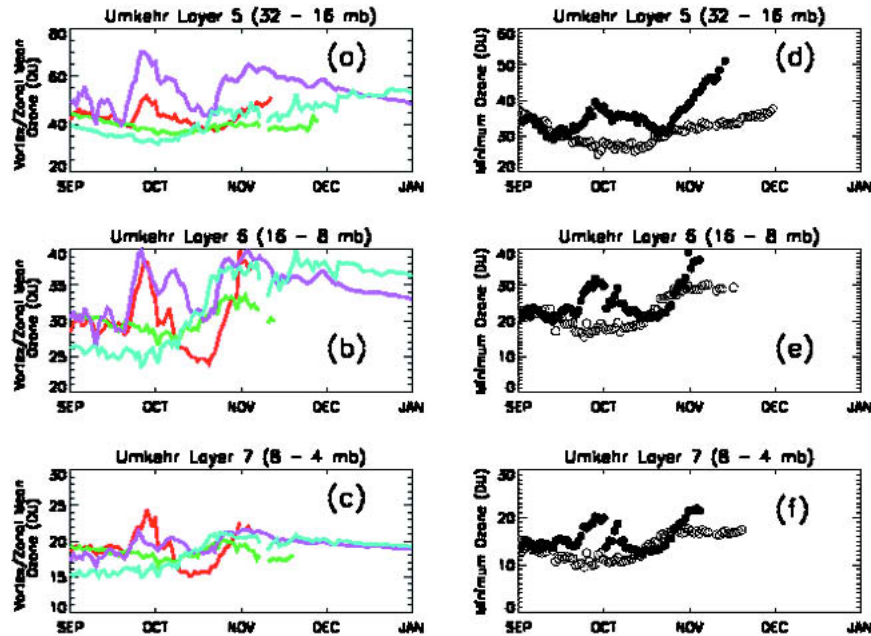


FIG. 5. The time series of SBUV/2 layer ozone amounts in DU for Umkehr layers 5, 6, and 7 in the middle and upper stratosphere. (a)–(c) Vortex-averaged and zonal mean ozone amounts. The zonal mean (70° – 80° S) are in pink for 2002 and blue for 2001. The vortex-averaged ozone data are in red for 2002 and green for 2001. To compute vortex-averaged ozone, the vortex was defined as the area encompassed by PV contours less than -160 , -300 , and -500 PVU for potential temperature surfaces 650 (layer 5), 850 (layer 6), and 1000 K (layer 7), respectively. (d)–(f) Time series of minimum ozone observed inside the vortex (closed circles for 2002 and open circles for 2001).

ing ratios as a function of height and latitude along the prime meridian (0° longitude) for a 5-day time period leading to the warming event show high ozone progressively shifting from low latitudes to high latitudes (see Fig. 6). Ozone mixing ratios are calculated from the SBUV/2 layer ozone retrievals by using a cubic spline fit to the X versus $\log p$ curve, where $X(p)$ is cumulative ozone amount above pressure p (Fleig et al. 1990). Figure 6 shows that on 20 September, low-ozone amounts between 60° S and the South Pole, corresponding to regions inside the vortex, are observed from 100 to 30 mb. This low-ozone region between 100 and 30 mb confined to the polar vortex gradually shrank over the 5-day period because of the displacement of the vortex into the midlatitudes and the filling in due to mixing with midlatitude high-ozone air. The propagation of high ozone near the 10-mb region from the midlatitudes to the polar region is evident in Fig. 6. Manney et al. (2005) report transport and descent of midlatitude ozone into the polar region between the 800- and 1100-K potential temperature surface. For example, between 40 and 30 mb, from 20 September to 25 September, ozone mixing ratios increase from 1 to 3 ppmv. Figure 7 shows the difference of zonal mean ozone mixing ratios between 25 and 20 September. One can see that most of the ozone enhancement occurred between 60 and 15 mb with peak increase centered around 30 mb.

This is consistent with ozonesonde observations that show similar increases in ozone between 127 and 16 mb (see Fig. 1). Assuming that ozone in this region is mostly controlled by dynamics and not by chemistry over a 5-day period, we infer that the bulk of the ozone transport and descent took place in the region between 60 and 15 mb. Manney et al. (2005) report that the transport and descent took place between the 800- and 1100-K potential temperature surface, that is, between 20 and 4 mb.

Although Figs. 6 and 7 show ozone profiles from 100 mb and above, only profiles from 32 mb and above have been integrated to obtain the SBUV/2 UOZ partial columns shown in Fig. 3. This is because the SBUV/2 algorithm is not capable of fully retrieving individual layer ozone changes below 32 mb (Fig. 1). Only 30% of the SBUV/2 total ozone increase seen in Fig. 2a was placed in the SBUV/2 UOZ partial column, of which the layer between 32 and 16 mb shows the largest increase. The increase in TOVS LOZ partial column ozone, on the other hand, is 50% of the total ozone increase seen in Fig. 2. This is probably an underestimate because TOVS has reduced sensitivity to ozone changes in the layer between 20 and 24 km during warm ozone surges (Neuendorffer 1996). Thus, of the 195 DU increase in total ozone observed during the warming of late September 2002, only a total of 80% is seen in the TOVS LOZ and SBUV/2 UOZ partial columns. It

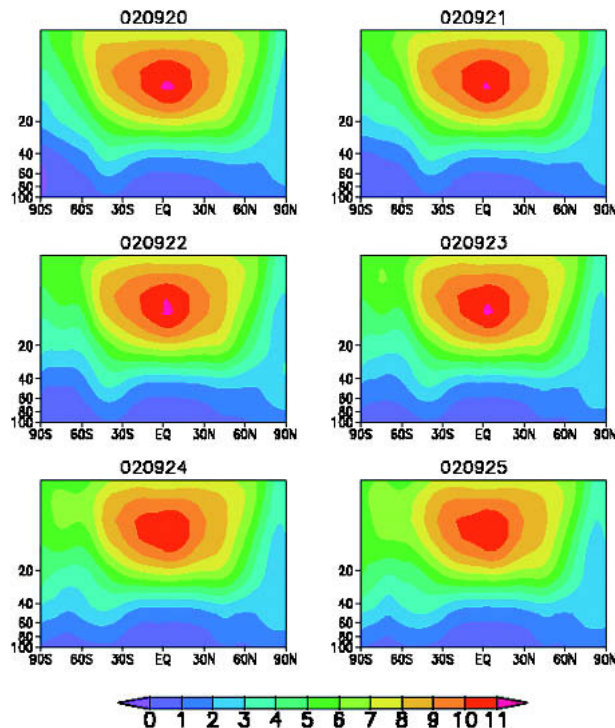


FIG. 6. Cross sections of SBUV/2 ozone mixing ratios as a function of height (pressure) and latitude along the prime meridian (0° longitude) for the 5-day time period leading to the warming event in Sep 2002. High ozone gradually propagates from low latitudes to high latitudes, shrinking and displacing the vortex as the event progresses.

should be noted that the warming events that result in a sudden ozone surge above the ozone density peak are unusual. Under normal conditions, the TOVS LOZ and SBUV/2 UOZ partial columns sum to the SBUV/2 total ozone very closely.

4. Vertical structure of the 2002 ozone hole

Although most of the ozone depletion takes place between 12 and 20 km during the ozone hole formation, the total column ozone is commonly used to monitor the size of the ozone hole. In the Southern Hemisphere mid- to high latitudes, areas with total column ozone below 220 DU are generally accepted to constitute ozone hole conditions (Newman et al. 1988; Schoeberl et al. 1986). The region between 12 and 20 km is where ozone-depleting chlorine activation takes place on the surface of the PSCs, which form when conditions are favorable [e.g., air temperatures below 196 K inside the isolated polar vortex (Dessler 2000)]. Since the bulk of the column ozone in the southern high latitudes normally resides in a region centered around 15 km, extensive ozone depletion between 12 and 20 km leads to low total column ozone values, and a minimum in lower stratospheric ozone coincides with a minimum in total ozone. For this scenario to hold, column ozone morphology must be dominated by chemical loss confined

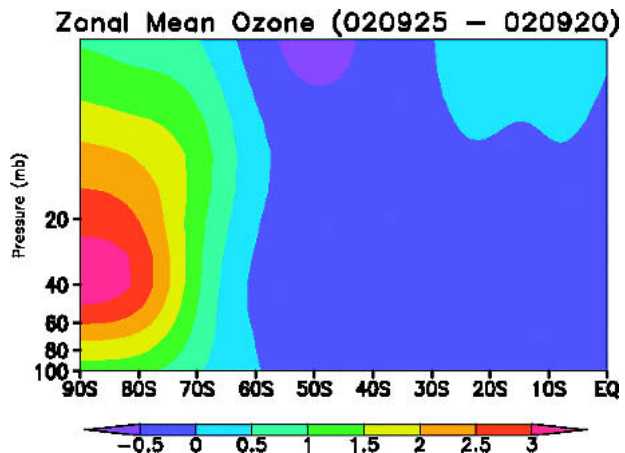


FIG. 7. Mixing ratio differences between zonal mean ozone mixing ratios (ppmv) observed on 25 and 20 Sep 2002 plotted as a function of height (pressure) and latitude. The net increase in ozone at high latitudes between 60 and 15 mb due to the warming is apparent. It should be noted that the changes in the observed ozone distribution represent the net effects of transport and chemistry.

to the vortex (Manney et al. 1996). Thus, monitoring total ozone as a measure of lower stratospheric ozone depletion over the Antarctic is reasonable, especially if ground-based ozonesonde observations can confirm the ozone depletion. In 2002, however, the late-September anomalous midstratospheric warming resulted in a polar vortex that was pushed off the Pole and split into two halves; total ozone values reached as high as 380 DU at the South Pole and close to 500 DU in the Eastern Hemisphere (Fig. 8). The ozone hole split into two distinct regions of low ozone, with an ozone-high region wedged in between. During the week of 24 September 2002, the polar vortex size near 70 mb (near 17 km) decreased from 25 to 16 million km^2 (Fig. 9a), the area occupied by PSC-producing temperatures decreased from 10 to 1 million km^2 (Fig. 9b), and the ozone hole area decreased from 18 to 3 million km^2 (Fig. 9c). Ozonesonde observations (available online at <http://www.cmdl.noaa.gov/ozwv/ozsondes/spo/ozppp2002.html>) from the South Pole and diagnostic analyses reported in section 3 indicate that the transport of high-ozone amounts occurred above the altitude where the effective ozone depletion takes place and concur with studies reported by Allen et al. (2003), Hoppel et al. (2003), Randall et al. (2005), and Manney et al. (2005). In such a situation, the conventional use of total column ozone to monitor lower stratospheric ozone depletion in the Southern Hemisphere breaks down because high ozone in the midstratosphere masks ozone depletion in the lower stratosphere. Although the size of the polar vortex dropped after the 25 September 2002 event, and its size was the smallest observed in the last 10 yr, TOVS LOZ retrievals (Fig. 10a) show that ozone within the lower stratospheric vortex was similar to that of 2001 (Fig. 10b). Inside the lower stratospheric vortex, ozone is primarily regulated by photochemistry, so it can be

SBUV/2 Total Ozone (September 25, 2002)

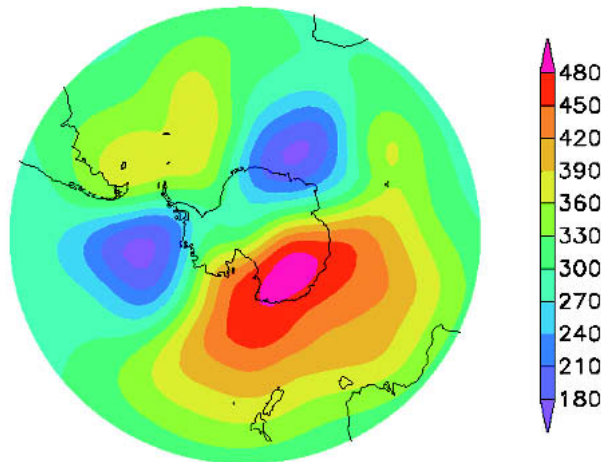


FIG. 8. The SBUV/2 total ozone map for the Southern Hemisphere in a polar stereographic projection on 25 Sep 2002, when the ozone hole appeared to split into two halves.

concluded that ozone depletion was similar to that in 2001. In fact, Hoppel et al. (2003) and Gross et al. (2005) show that until major warming, chemical ozone depletion in 2002 was similar to the depletion in previous years. The vortex in the lower stratosphere was elongated but not completely split, unlike that suggested by the total column ozone map shown in Fig. 8. TOVS LOZ amounts on 25 September 2002 were still low inside the vortex (identified by PV at 450 K < -32), and the vortex was shifted from the center of the Pole and elongated into two distinct lobes. TOVS LOZ amounts were lower on one side of the vortex (bigger lobe) than on the other but were similar to those observed in 2001. In 2001, TOVS LOZ ozone amounts were between 20 and 40 DU over the entire Antarctic continent (Fig. 10b), whereas in 2002, TOVS LOZ ozone amounts were between 20 and 50 DU in the bigger lobe (Fig. 10a). This is because of differences in vortex size and shape between the two years and weakening of the vortex on one side (note that the smaller lobe diminished soon after the warming event and only the larger lobe survived). On 25 September 2001, the polar vortex was symmetrical and occupied $\sim 32 \times 10^6$ km², whereas in 2002 the vortex was split and occupied only $\sim 20 \times 10^6$ km² (Fig. 9). On the smaller side of the elongated vortex, TOVS LOZ ozone amounts were between 50 and 70 DU (Fig. 10a); higher values are probably due to cross-vortex mixing. According to SBUV/2 UOZ retrievals, the stratospheric ozone between 24 and 54 km also has low-ozone regions on the two ends of the nearly split vortex. It should be noted that we excluded the SBUV/2 layer retrieval between 63 and 32 mb (19 to 24 km) from the SBUV/2 UOZ because individual layer ozone changes below 24 km are not resolvable by the SBUV/2 algorithm (Bhartia et al. 1996). Figure 10a shows that the ozone features in the lower

stratosphere (TOVS LOZ) were not aligned with ozone features in the mid- to upper stratosphere (SBUV/2 UOZ). Figure 10b shows that they were very closely aligned in 2001. The vertical misalignment of the vortices in the lower stratosphere and upper stratosphere led to higher integrated column values masking the lower-stratospheric ozone depletion inside the vortex and resulting in a smaller ozone hole as defined by the standard criterion (area confined to total ozone < 220 DU). The vertical misalignment of the vortices also resulted in a 2002 ozone hole that appeared to be split, when in fact, the polar vortex with the ozone-depleted region in the lower stratosphere was elongated but not split.

Synoptic evolution of the major warming event that

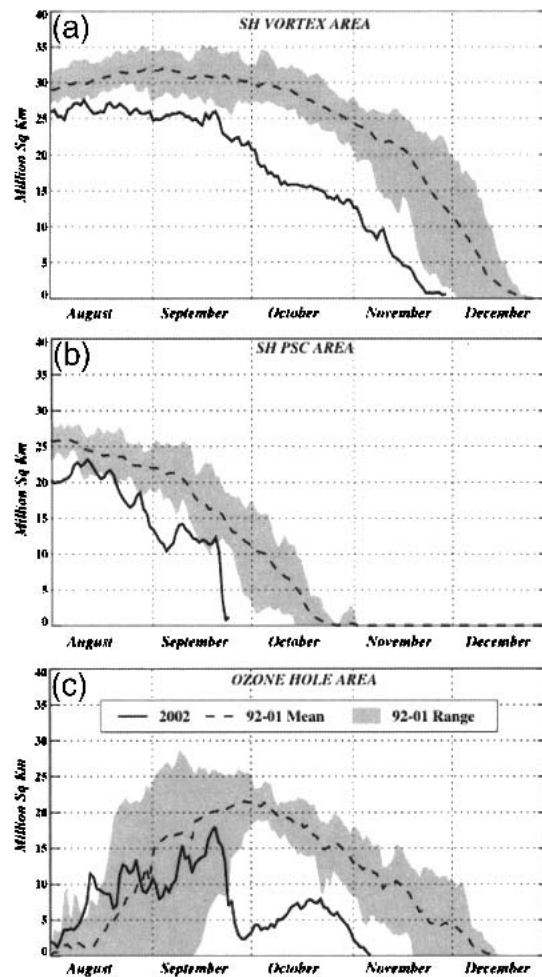


FIG. 9. (a) Size of the Southern Hemisphere polar vortex (defined as enclosed area by 32-PVU contour at the 450-K isentropic surface), (b) size of the region with temperatures $< -78^{\circ}\text{C}$ (also on the 450-K isentropic surface) from National Centers for Environmental Prediction (NCEP) analysis, and (c) the time series of the area of the 2002 ozone hole (total ozone < 220 DU) as observed by SBUV/2. The shaded region illustrates the range of areas over the past 10 yr. The dashed line is the daily mean area for the previous 10 yr.

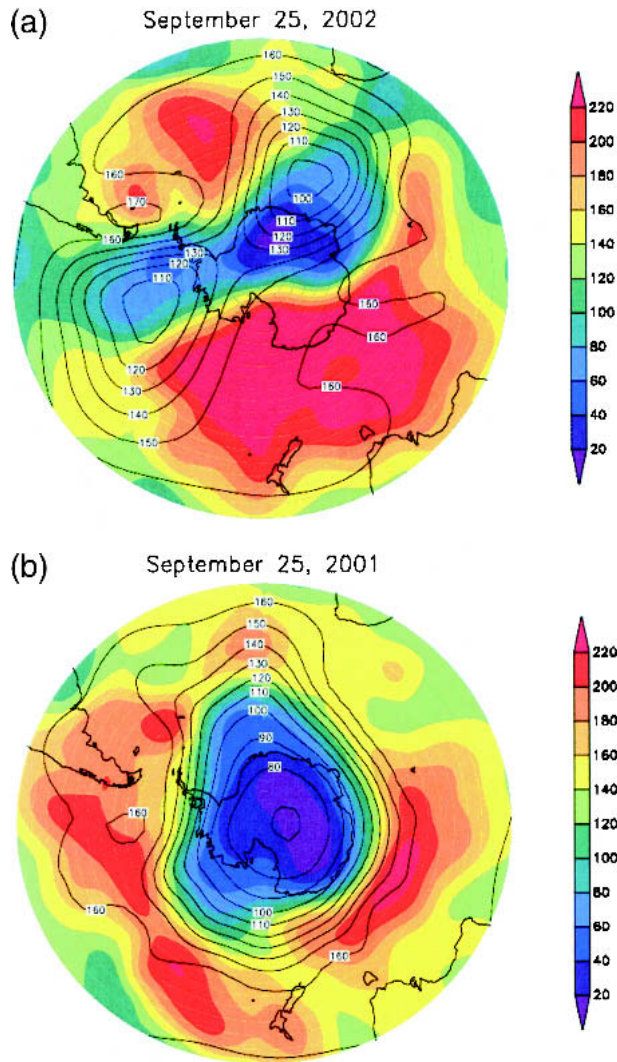


FIG. 10. Maps of TOVS partial column between 0 and 24 km (LOZ), shown in color at an interval of 20 DU, and SBUV/2 partial column between 24 and 54 km (UOZ), shown in contours at an interval of 10 DU: (a) 25 Sep 2002 and (b) 25 Sep 2001. Note that UOZ and LOZ are fairly well aligned with each other in 2001 but not in 2002.

led to the vertical misalignment of the lower stratosphere and midstratosphere vortices are shown in Fig. 11. The three columns illustrate the movement of the polar vortex in the lower stratosphere (TOVS LOZ) and mid- to upper stratosphere (SBUV/2 ozone mixing ratios at different pressure levels) over a 5-day period. For each day, the rows show ozone amounts at different pressure levels (3, 10, 30 mb), TOVS LOZ, and SBUV/2 total ozone. On 21 September, the ozone field in the lower stratosphere (TOVS LOZ) was beginning to show distortions with ozone gradients inside the vortex. The PV map for the same day at the 450-K potential temperature surface shows similar features (figure not shown). Ozone mixing ratios at the three SBUV/2

pressure levels show that the low-ozone regions were slightly elongated and shifted from the Pole with the extravortex high-ozone region creeping into the Antarctic continent. Due to the misalignment of the low-ozone regions at different heights, the area occupied by the ozone hole was estimated to be only 16 million km².

On 23 September, the low-ozone region in the TOVS LOZ map is tilted eastward with ozone amounts much lower on one side compared to the other, with the narrow part of the low-ozone region containing ozone amounts as high as 90 DU. The low-ozone region in the SBUV/2 UOZ maps in the upper layers is elongated further with distinct low-ozone regions. The low-ozone regions are much more misaligned than those on 21 September, and the ozone hole area was estimated to be 13×10^6 km². Although not completely split, the SBUV/2 total ozone map begins to show elongation.

By 25 September, the total ozone map indicates a split vortex. However, the TOVS LOZ map shows an elongated but intact low-ozone region indicating an elongated vortex. The SBUV/2 UOZ amounts near 30 mb form two distinct lobes with high ozone forming a wedge between the two lobes. The 10-mb low-ozone region in the SBUV/2 UOZ map indicates a vortex with two distinct lobes but not completely split; it has a semicircle shape with low ozone throughout. The left side of the semicircle-shaped vortex was eroded at 3 mb. The estimated ozone hole area on 25 September was 8×10^6 km².

By 29 September 2002, the smaller part of the split vortex dissipated (figure not shown), and the estimated ozone hole area was at a minimum of 2.3×10^6 km². The bigger part of the split vortex moved back to the center of the Antarctic continent after which the vortex remained stable, and the size of the ozone hole started to increase for a while; it was nearly 8×10^6 km² on 22 October 2002. Then the area of the ozone hole decreased, and it dissipated completely by 9 November 2002.

5. Conclusions

The ozone surge over the Antarctic continent due to the major Southern Hemisphere warming in late September 2002 was a record high for SBUV (/2) observations, which date back to 1979. Daily zonal mean total ozone for 70°–80°S increased to ~385 DU during the week of 24 September 2002. This value is higher than any values observed in the preozone hole years of 1979–82 for the month of September. In a matter of just 5 days, between 21 and 25 September, zonal mean ozone increased by 195 DU due to the transport of high ozone from low latitudes. The SBUV/2 data indicate that the ozone increase was most dramatic between 60 and 15 mb. As observed by TOVS LOZ, low-ozone values inside the lower-stratospheric vortex are consistent with the analysis of Hoppel et al. (2003) that showed that chemical ozone depletion induced by chlorine activation inside the 2002 polar vortex was similar to the depletion in 2001 until the weakening and early breakup of the vortex. Even though the vortex was

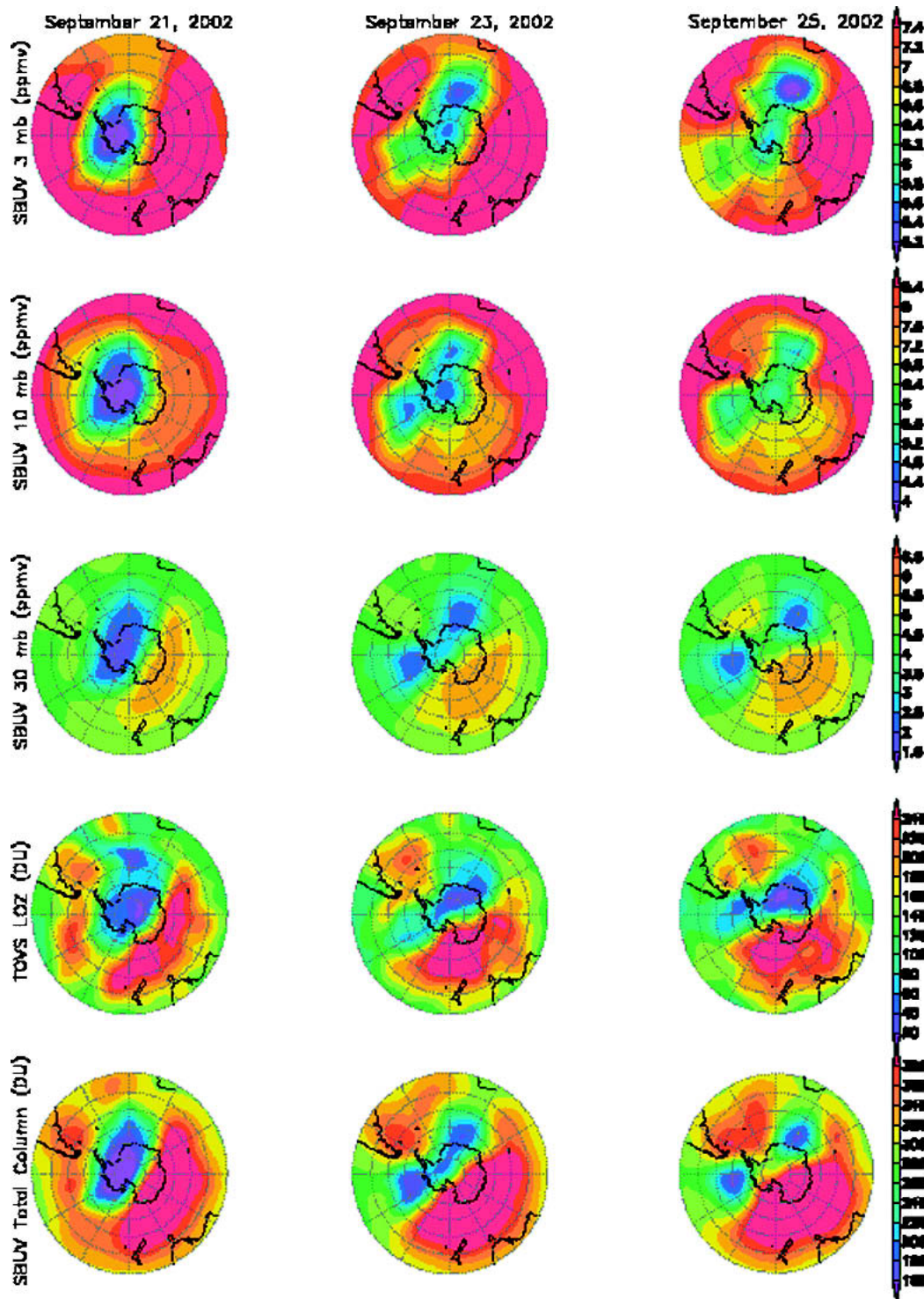


FIG. 11. Vertical profiles of ozone distributions in polar stereographic projection for 21, 23, and 25 Sep 2002. Deep purple indicates regions with low-ozone values inside the polar vortex.

pushed off the Pole and distorted, the ozone values inside the polar vortex in the lower stratosphere remained between 20 and 40 DU. The difference between the two years is the size, shape, and position of the

polar vortex. In 2001, the vortex was centered around the Pole and covered the entire Antarctic continent, while in 2002 it was pushed off of the Pole and elongated due to the warming event, with TOVS LOZ val-

ues much lower on one side of the lobe than the other. The TOVS LOZ and SBUV/2 UOZ distributions in the different layers of the middle and upper stratosphere indicate that the polar vortex was elongated but intact in the lower stratosphere but split into two distinct lobes in the middle stratosphere. However, the vortex-averaged TOVS LOZ amounts indicate cross-vortex mixing of high ozone on the smaller side of the elongated vortex. The SBUV/2 UOZ amounts indicate significant cross-vortex mixing in the middle and upper stratosphere. During the warming event in late September, the polar vortex in the lower stratosphere was not vertically aligned with the vortex in the middle and upper stratosphere. The SBUV/2 UOZ and TOVS LOZ amounts follow the vortex structure in the middle and upper stratosphere, which was rotated by nearly 45° relative to the vortex in the lower stratosphere on certain days during the late-September 2002 warming event. The offset between the vortices in the lower stratosphere and midstratosphere masked the ozone depletion in the lower stratosphere and resulted in higher total column ozone and a smaller ozone hole estimate. The average size of the 2002 ozone hole for October and November was $3.5 \times 10^6 \text{ km}^2$, which is larger than both the $1.5 \times 10^6 \text{ km}^2$ in 1988 and $1.2 \times 10^6 \text{ km}^2$ in 1982 but much smaller than the $16.4 \times 10^6 \text{ km}^2$ observed in 1998.

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